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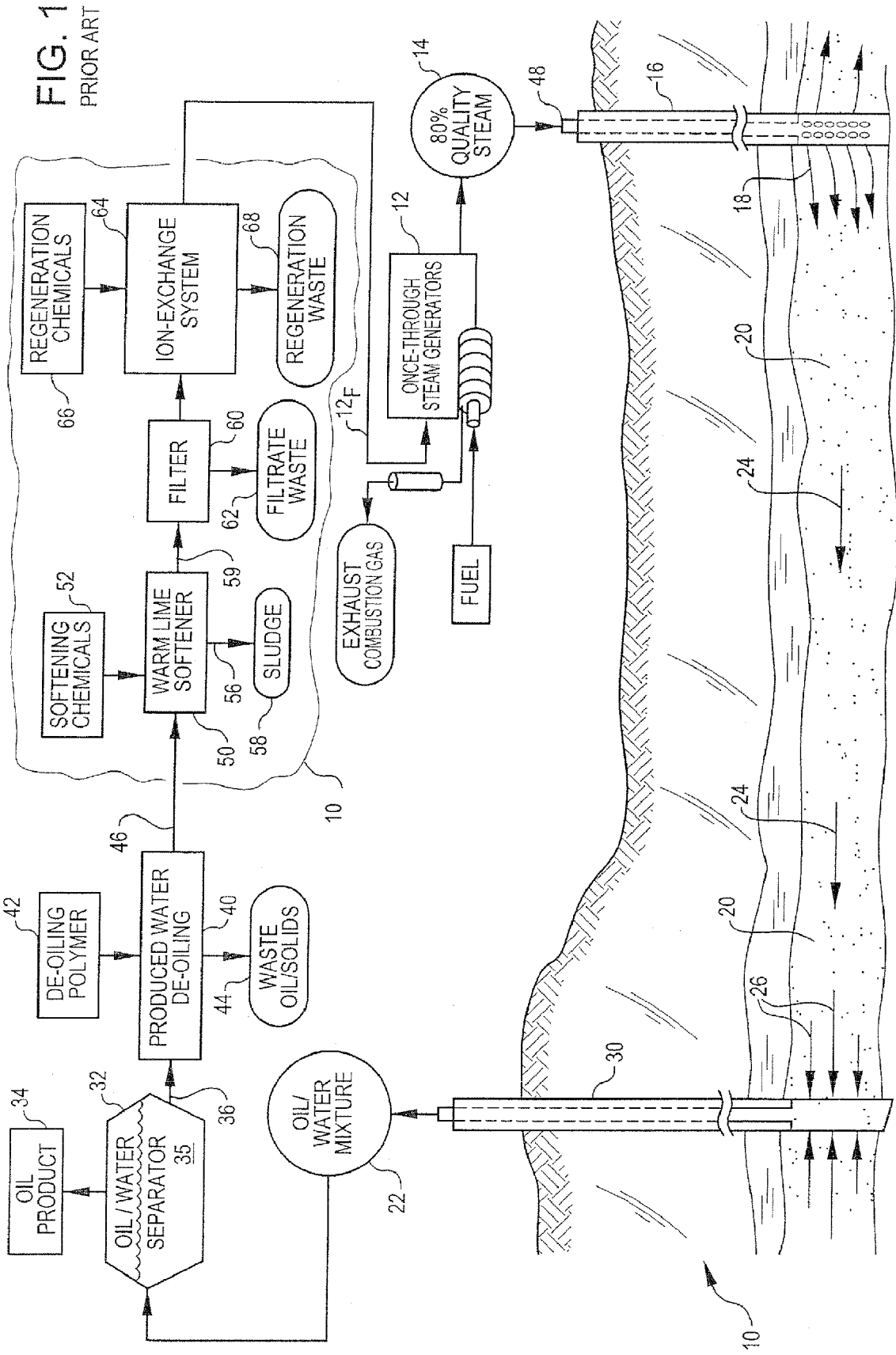


FIG. 1
PRIOR ART

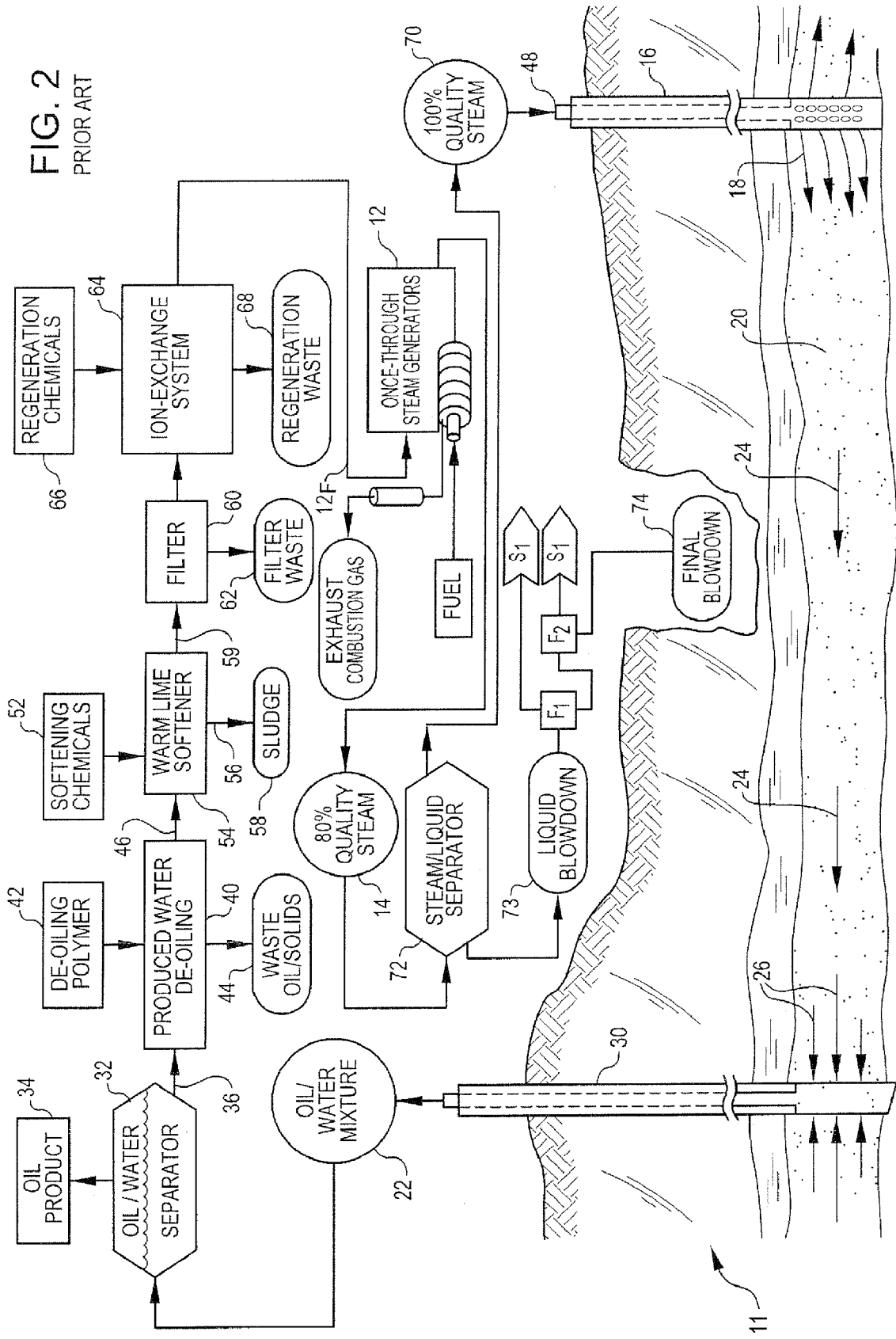


FIG. 2
PRIOR ART

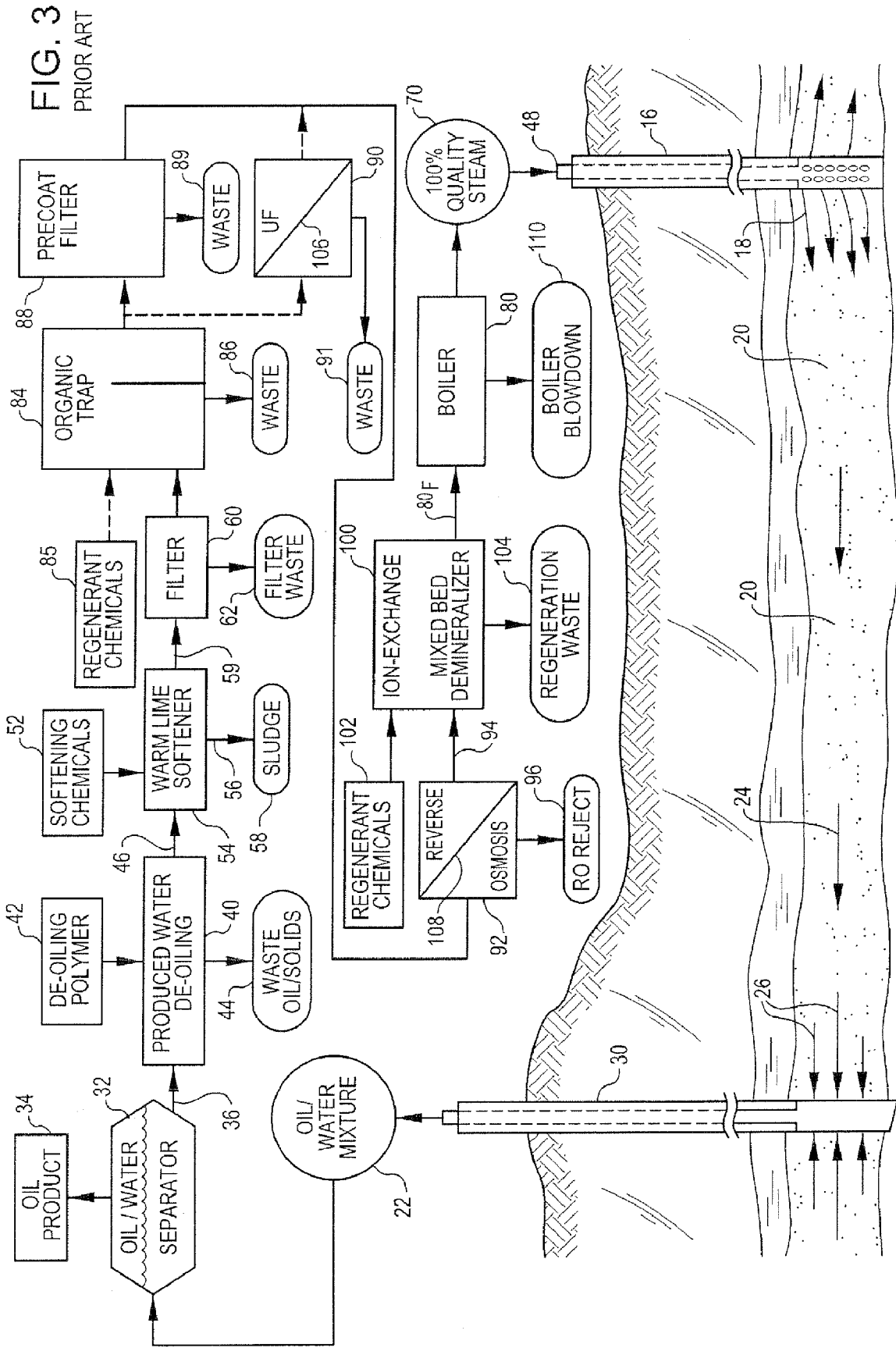
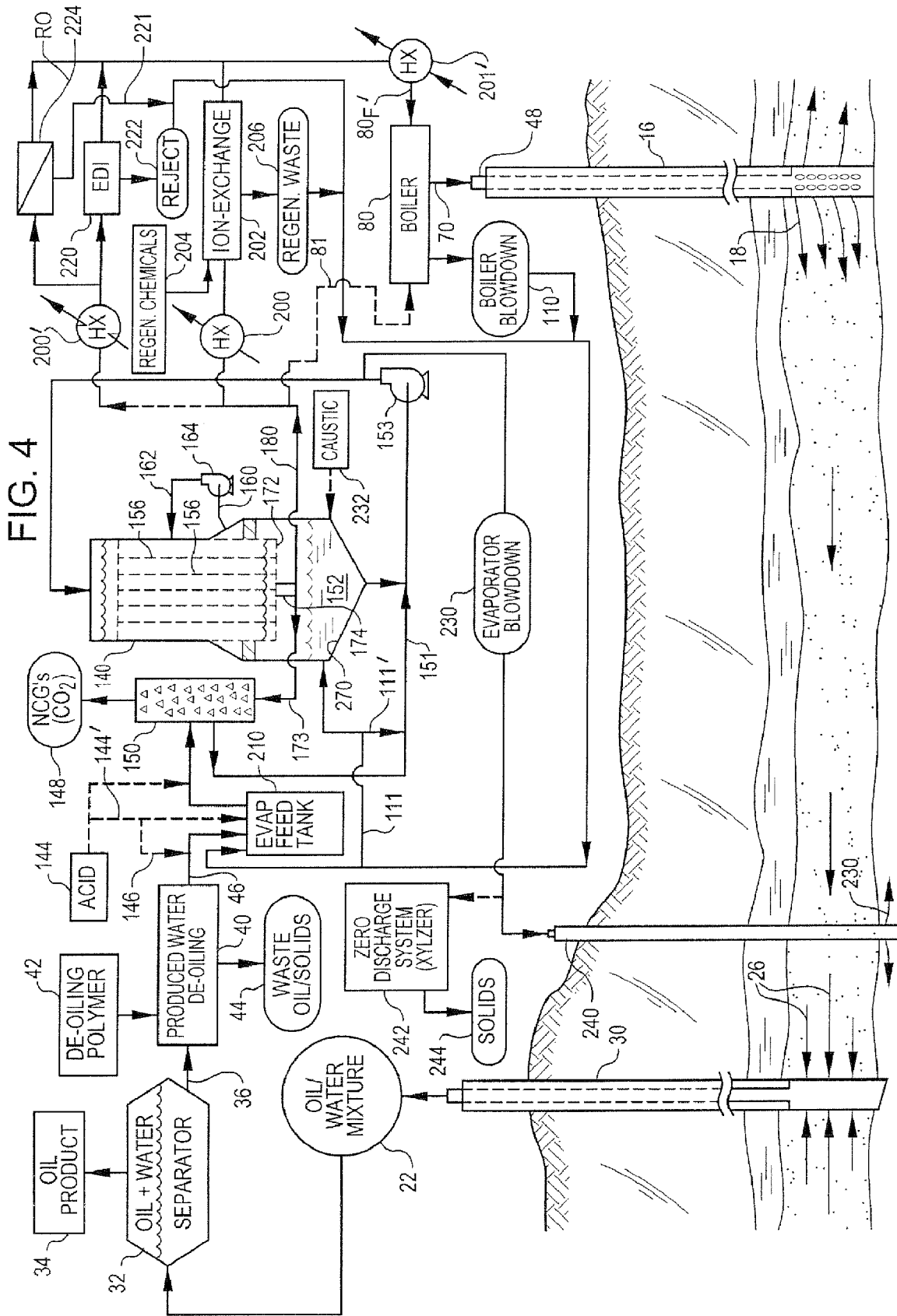


FIG. 3
PRIOR ART



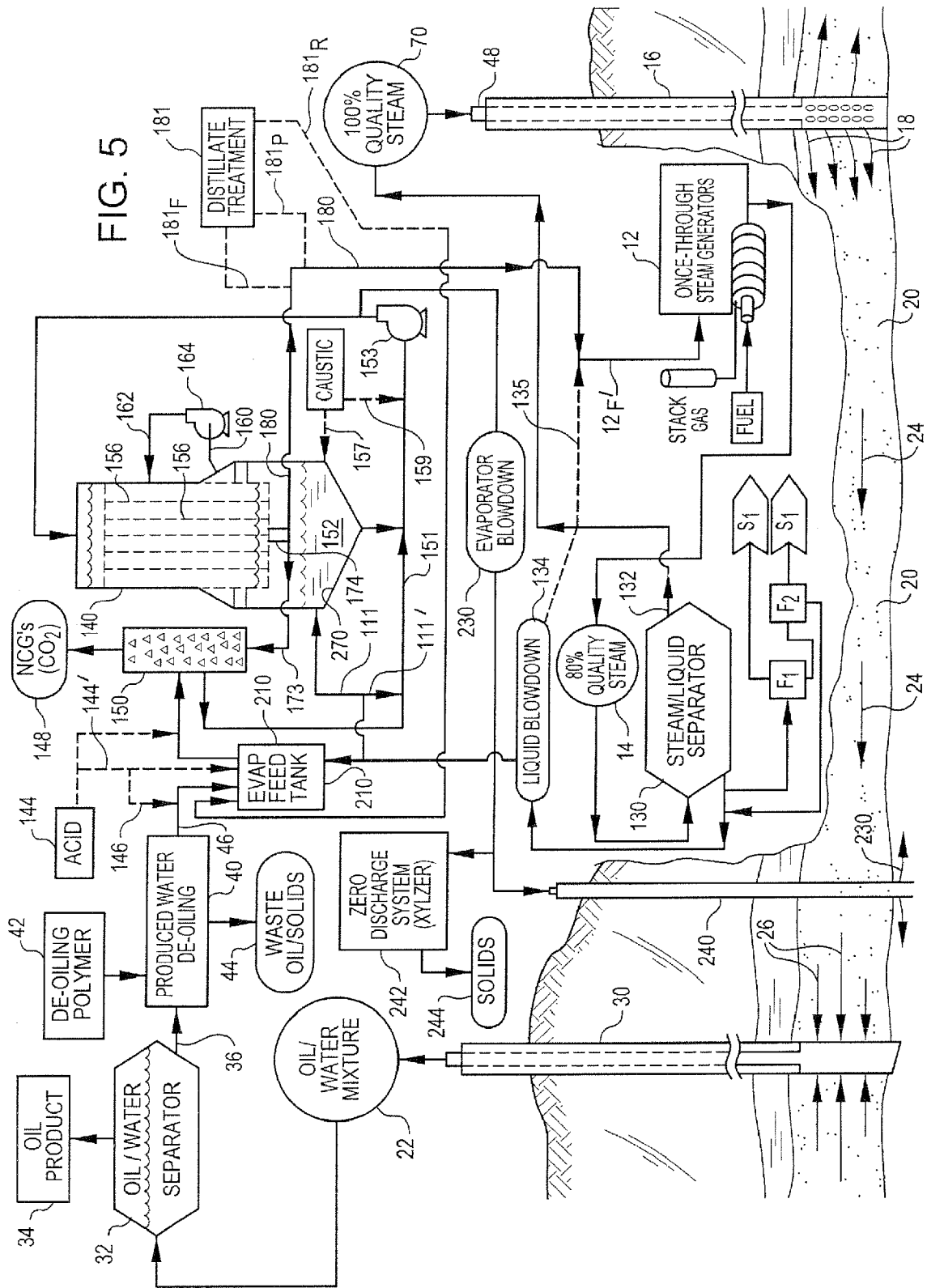


FIG. 6

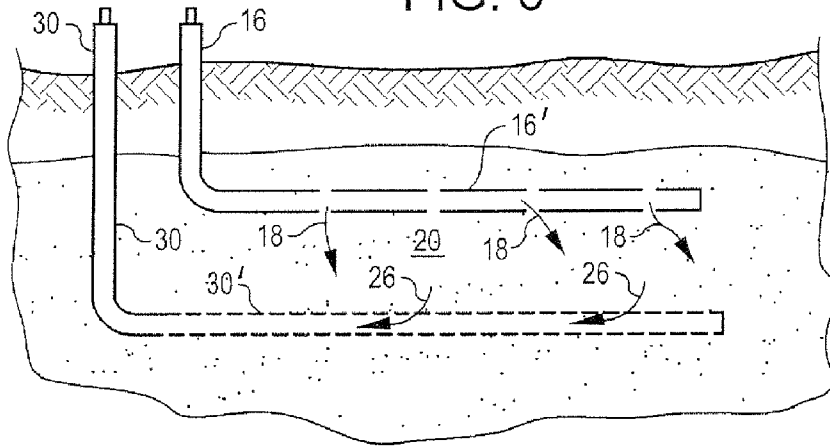


FIG. 7

TYPICAL FEEDWATER REQUIREMENTS

Constituent	Packaged	
	Boilers	Units
Hardness	< 0.05 mg/l	as CaCO ₃ *
Non-volatile TOC	< 0.20 mg/l	as C
Oil & Grease	< 0.20 mg/l	as substance
pH	8.8 to 9.6	pH
Cu	< 0.01 mg/l	as Cu
Fe	< 0.01 mg/l	as Fe
O ₂	< 0.007 mg/l	as O ₂
* Hardness	Non-detectable when P>1000psig	

FIG. 8

TYPICAL FEEDWATER REQUIREMENTS

Constituent	ONCE-THROUGH	
	Steam Generators	Units
Hardness	< 1.0 mg/L	as CaCO ₃
Non-volatile TOC	Reasonable	as C
Oil & Grease	< 0.5 mg/L	as substance
pH	7.5 to 9.0	pH
TDS	< 12,000 mg/L	as CaCO ₃ equivalent
O ₂	negligible	as O ₂ as
Fe	<0.25 mg/L	as Fe
SiO ₂	<100mg/L	as SiO ₂

FIG. 9

SIMPLIFIED VAPOR COMPRESSION FALLING FILM EVAPORATOR SYSTEM

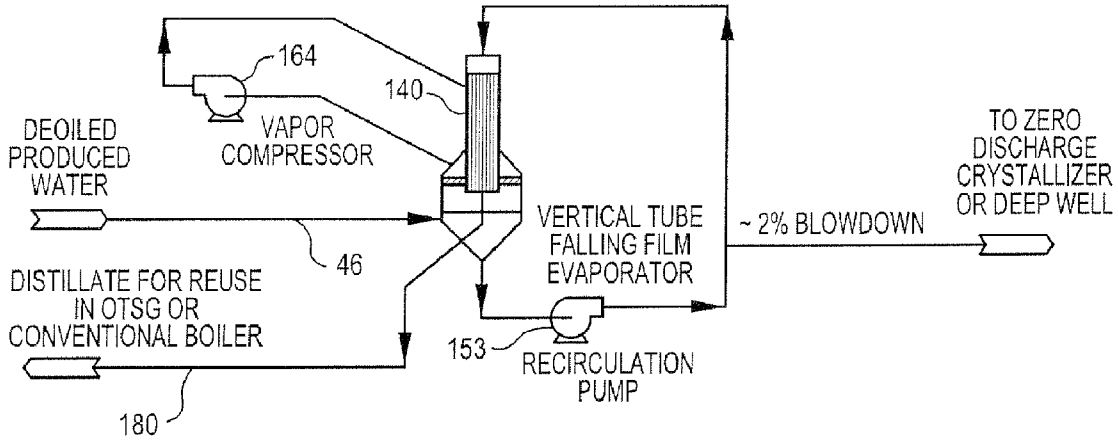


FIG. 10

VERTICAL TUBE FALLING FILM VAPOR COMPRESSION EVAPORATOR SCHEMATIC

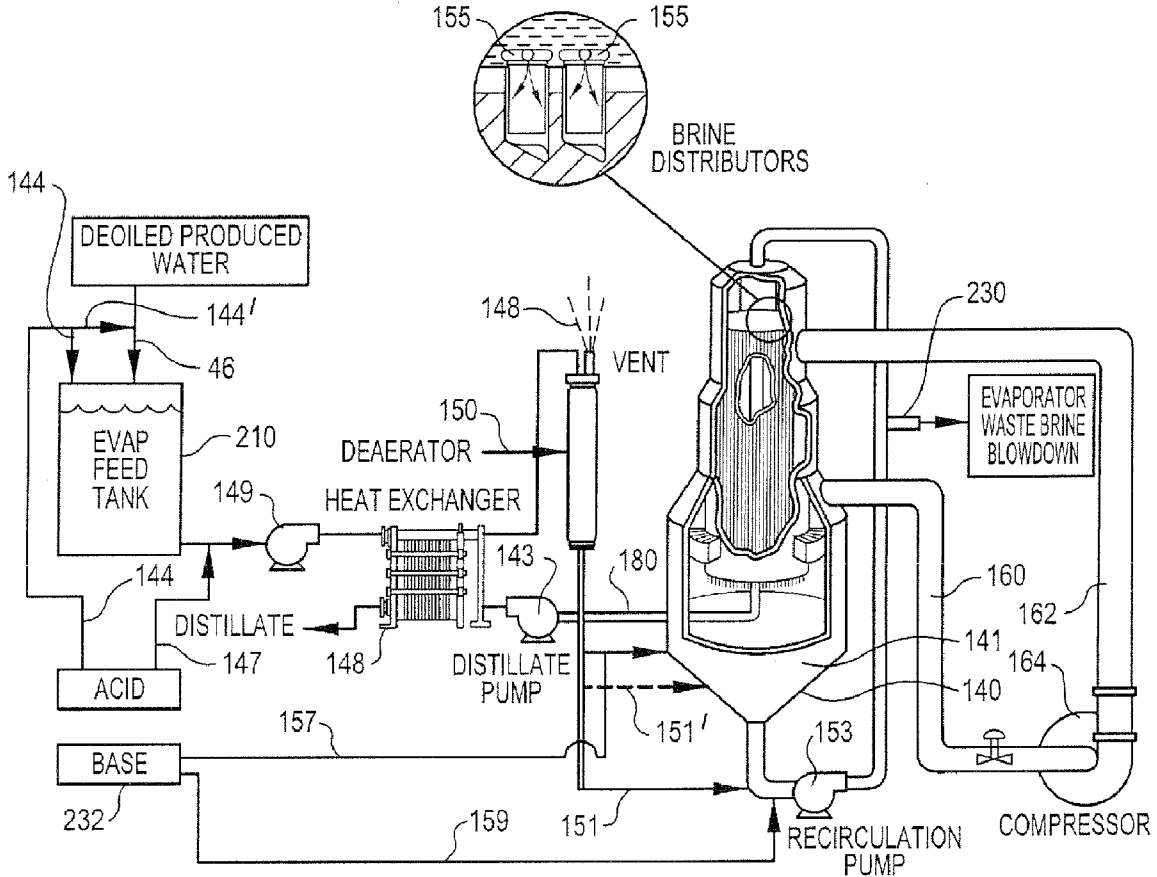


FIG. 11
SILICA SOLUBILITY CHARACTERISTICS

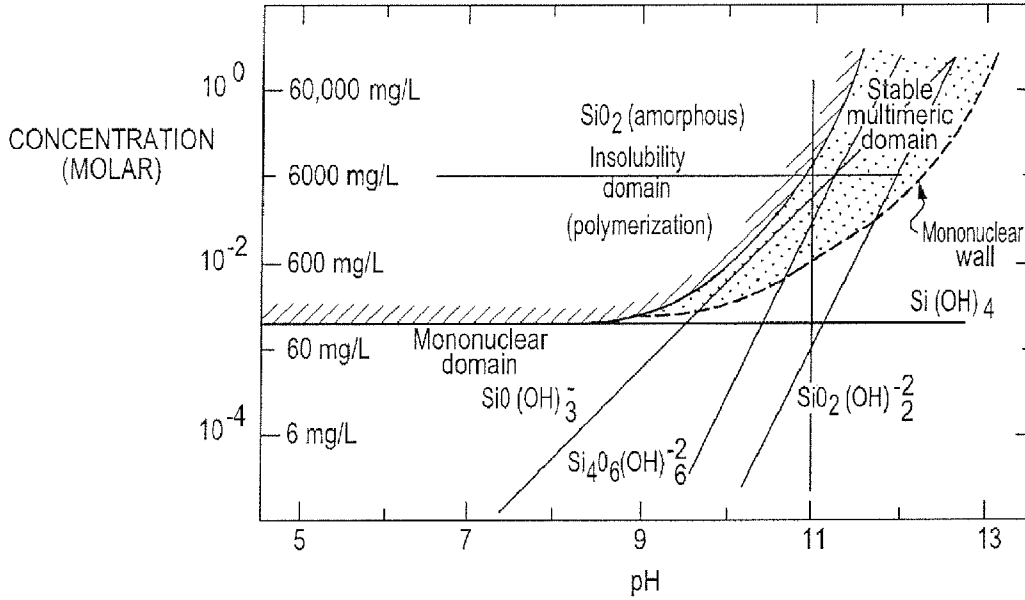
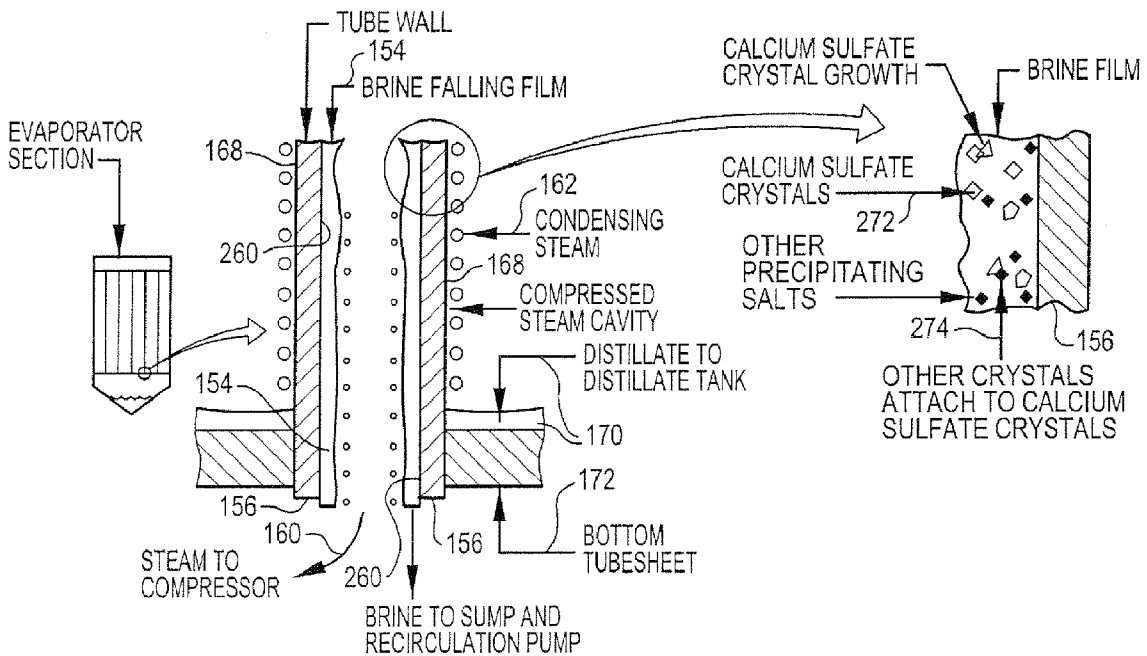


FIG. 12
SEEDED-SLURRY SCALE PREVENTION MECHANISM



WATER TREATMENT METHOD FOR HEAVY OIL PRODUCTION USING CALCIUM SULFATE SEED SLURRY EVAPORATION

RELATED PATENT APPLICATIONS

This application is a Divisional of U.S. patent application Ser. No. 11,149,072, filed Jun. 8, 2005, issued on Oct. 21, 2008 as U.S. Pat. No. 7,438,129, which was a Continuation-In-Part of prior U.S. patent application Ser. No. 10/868,745, filed Jun. 9, 2004, now U.S. Pat. No. 7,150,320B2 issued Dec. 19, 2006, entitled WATER TREATMENT METHOD FOR HEAVY OIL PRODUCTION, which was a Continuation-In-Part of prior U.S. patent application Ser. No. 10/307,250, filed Nov. 30, 2002, now U.S. Pat. No. 7,077,201B2 issued Jul. 18, 2006, entitled WATER TREATMENT METHOD FOR HEAVY OIL PRODUCTION, which was a Continuation-In-Part of prior U.S. patent application Ser. No. 09/566,622, filed May 8, 2000, now U.S. Pat. No. 6,733,636B1 issued May 11, 2004, entitled WATER TREATMENT METHOD FOR HEAVY OIL PRODUCTION, which claimed priority from prior U.S. Provisional Patent Application Ser. No. 60/133,172, filed on May 7, 1999. Also, U.S. patent application Ser. No. 11/149,072 claimed priority from U.S. Provisional Patent Application Ser. No. 60/578,810, filed Jun. 9, 2004. The disclosures of each of the above identified patents or patent applications are incorporated herein in their entirety by this reference, including the specification, drawing, and claims of each patent or application.

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TECHNICAL FIELD

The invention disclosed and claimed herein relates to treatment of water to be used for steam generation in operations which utilize steam to recover oil from geological formations. More specifically, this invention relates to novel, improved techniques for efficiently and reliably generating from oil field produced waters, in high pressure steam generators, the necessary steam for down-hole use in heavy oil recovery operations.

BACKGROUND

Steam generation is necessary in heavy oil recovery operations. This is because in order to recover heavy oil from certain geologic formations, steam is required to increase the mobility of the sought after oil within the formation. In prior art systems, oil producers have often utilized once-through type steam generators ("OTSG's). As generally utilized in the industry, once through steam generators—OTSG's—usually have high blowdown rates, often in the range of from about 20% to about 30% or thereabouts. Such a blowdown rate leads to significant thermal and chemical treatment inefficiencies. Also, once through steam generators are most commonly provided in a configuration and with process parameters so that steam is generated from a feedwater in a single-pass operation through boiler tubes that are heated by gas or

oil burners. Typically, such once through steam generators operate at from about 1000 pounds per square inch gauge (psig) to about 1600 psig or so. In some cases, once through steam generators are operated at up to as much as about 1800 psig. Such OTSG's often operate with a feedwater that has from about 2000 mg/L to about 8000 mg/L of total dissolved solids. As noted in FIG. 1, which depicts the process flow sheet of a typical prior art water treatment system 10, such a once through steam generator 12 provides a low quality or wet steam, wherein about eighty percent (80%) quality steam is produced. In other words, the 80% quality steam 14 is about 80% vapor, and about 20% liquid, by weight percent. The steam portion, or high pressure steam produced in the steam generators is injected via steam injection wells 16 to fluidize as indicated by reference arrows 18, along or in combination with other injectants, the heavy oil formation 20, such as oils in tar sands formations. The injected steam 14 eventually condenses and an oil/water mixture 22 results, and which mixture migrates through the formation 20 as indicated by reference arrows 24. The oil/water mixture 22 is gathered as indicated by reference arrows 26 by oil/water gathering wells 30, through which the oil/water mixture is pumped to the surface. Then, the sought-after oil is sent to an oil/water separator 32 in which the oil product 34 separated from the water 35 and recovered for sale. The produced water stream 36, after separation from the oil, is further de-oiled in a de-oiling process step 40, normally by addition of a de-oiling polymer 42 or by other appropriate processes. Such a de-oiling process usually results in generation of an undesirable waste oil/solids sludge 44. However, the de-oiled produced water stream 46 is then further treated for reuse.

The design and operation of the water treatment plant which treats the de-oiled produced water stream 46, i.e., downstream of the de-oiling unit 40 and upstream of injection well 16 inlet 48, is the key to the improvement(s) described herein.

Most commonly in prior art plants such as plant 10, the water is sent to the "once-through" steam generators 12 for creation of more steam 14 for oil recovery operations. The treated produced water stream 12F which is the feed stream for the once through steam generator, at time of feed to the steam generator 12, is typically required to have less than about 8000 parts per million ("PPM") of total dissolved solids ("TDS"). Less frequently, the treated produced water stream 12F may have up to about 12000 parts per million (as CaCO₃ equivalent) of total dissolved solids, as noted in FIG. 8. Further, it is often necessary to meet other specific water treatment parameters before the water can be reused in such once-through steam generators 12 for the generation of high pressure steam.

In most prior art water treatment schemes, the de-oiled recovered water 46 must be treated in a costly water treatment plant sub-system 10₁ before it can be sent to the steam generators 12. Treatment of water before feed to the once-through steam generators 12 is often initially accomplished by using a warm lime softener 50, which removes hardness, and which also removes some silica from the de-oiled produced water feedstream 46. Various softening chemicals 52 are usually necessary, such as lime, flocculating polymer, and perhaps soda ash. The softener clarifier 54 underflow 56 produces a waste sludge 58 which must be further handled and disposed. Then, an "after-filter" 60 is often utilized on the clarate stream 59 from the softener clarifier 54, to prevent carry-over from the softener clarifier 54 of any precipitate or other suspended solids, which substances are thus accumulated in a filtrate waste stream 62. For polishing, an ion exchange step 64, normally including a hardness removal step

such as a weak acid cation (WAC) ion-exchange system that can be utilized to simultaneously remove hardness and the alkalinity associated with the hardness, is utilized. The ion exchange systems **64** require regeneration chemicals **66** as is well understood by those of ordinary skill in the art and to which this disclosure is directed. As an example, however, a WAC ion exchange system is usually regenerated with hydrochloric acid and caustic, resulting in the creation of a regeneration waste stream **68**. Overall, such prior art water treatment plants are relatively simple, but, result in a multitude of liquid waste streams or solid waste sludges that must be further handled, with significant additional expense.

In one relatively new heavy oil recovery process, known as the steam assisted gravity drainage heavy oil recovery process (the "SAGD" process), it is preferred that one hundred percent (100%) quality steam be provided for injection into wells (i.e., no liquid water is to be provided with the steam to be injected into the formation). Such a typical prior art system **11** is depicted in FIG. 2. However, given conventional prior art water treatment techniques as just discussed in connection with FIG. 1, the 100% steam quality requirement presents a problem for the use of once through steam generators **12** in such a process. That is because in order to produce 100% quality steam **70** using a once-through type steam generator **12**, a vapor-liquid separator **72** is required to separate the liquid water from the steam. Then, the liquid blowdown **73** recovered from the separator is typically flashed several times in a series of flash tanks F_1, F_2, \dots, F_N (where N is a positive integer equal to the number of flash tanks) to successively recover as series of lower pressure steam flows S_1, S_2, \dots , etc. which may sometimes be utilized for other plant heating purposes. After the last flashing stage F_N , a residual hot water final blowdown stream **74** must then be handled, by recycle and/or disposal. The 100% quality steam is then sent down the injection well **16** and injected into the desired formation **20**. Fundamentally, though, conventional treatment processes for produced water used to generate steam in a once-through steam generator produces a boiler blowdown which is roughly twenty percent (20%) of the feedwater volume. This results in a waste brine stream that is about fivefold the concentration of the steam generator feedwater. Such waste brine stream must be disposed of by deep well injection, or if there is limited or no deep well capacity, by further concentrating the waste brine in a crystallizer or similar system which produces a dry solid for disposal.

As depicted in FIG. 3, another method which has been proposed for generating the required 100% quality steam for use in the steam assisted gravity drainage process involves the use of boilers **80**, which may be packaged, factory built boilers of various types or field assembled boilers with mud and steam drums and water wall piping. Various methods can be used for producing water of a sufficient quality to be utilized as feedwater **80F** to a boiler **80**. One method which has been developed for use in heavy oil recovery operations involves de-oiling **40** of the produced water **36**, followed by a series of physical-chemical treatment steps. Such treatment steps normally include a series of unit operations as warm lime softening **54**, followed by filtration **60** for removal of residual particulates, then an organic trap **84** (normally non-ionic ion exchange resin) for removal of residual organics. The organic trap **84** may require a regenerant chemical supply **85**, and, in any case, produces a waste **86**, such as a regenerant waste. Then, a pre-coat filter **88** can be used, which has a precoat filtrate waste **89**. In one alternate embodiment, an ultrafiltration ("UF") unit **90** can be utilized, which unit produces a reject waste stream **91**. Then, effluent from the UF unit **90** or precoat filter **88** can be sent to a reverse osmosis ("RO")

system **92**, which in addition to the desired permeate **94**, produces a reject liquid stream **96** that must be appropriately handled. Permeate **94** from the RO system **92**, can be sent to an ion exchange unit **100**, typically but not necessarily a mixed bed demineralization unit, which of course requires regeneration chemicals **102** and which consequently produces a regeneration waste **104**. And finally, the boiler **80** produces a blowdown **110** which must be accommodated for reuse or disposal.

The prior art process designs, such as depicted in FIG. 3, for utilizing packaged boilers in heavy oil recovery operations, have a high initial capital cost. Also, such a series of unit process steps involves significant ongoing chemical costs. Moreover, there are many waste streams to discharge, involving a high and ongoing sludge disposal cost. Further, where membrane systems such as ultrafiltration **90** or reverse osmosis **92** are utilized, relatively frequent replacement of membranes **106** or **108**, respectively, may be expected, with accompanying on-going periodic replacement costs. Also, such a process scheme can be labor intensive to operate and to maintain.

In summary, the currently known and utilized methods for treating heavy oil field produced waters in order to generate high quality steam for down-hole use are not entirely satisfactory because:

- such physical-chemical treatment process schemes are usually quite extensive, are relatively difficult to maintain, and require significant operator attention;
- such physical-chemical treatment processes require many chemical additives which must be obtained at considerable expense, and many of which require special attention for safe handling;
- such physical-chemical treatment processes produce substantial quantities of undesirable sludges and other waste streams, the disposal of which is increasingly difficult, due to stringent environmental and regulatory requirements.

It is clear that the development of a simpler, more cost effective approach to produced water treatment would be desirable in the process of producing steam in heavy oil production operations. Thus, it can be appreciated that it would be advantageous to provide a new produced water treatment process which minimizes the production of undesirable waste streams, while minimizing the overall costs of owning and operating a heavy oil recovery plant.

SOME OBJECTS, ADVANTAGES, AND NOVEL FEATURES

The new water treatment process(es) disclosed herein, and various embodiments thereof, can be applied to heavy oil production operations. Such embodiments are particularly advantageous in that they minimize the generation of waste products, and are otherwise superior to water treatment processes heretofore used or proposed in the recovery of bitumen from tar sands or other heavy oil recovery operations.

From the foregoing, it will be apparent to the reader that one of the important and primary objectives resides in the provision of a novel process, including several variations thereof, for the treatment of produced waters, so that such waters can be re-used in producing steam for use in heavy oil recovery operations.

Another important objective is to simplify process plant flow sheets, i.e., minimize the number of unit processes required in a water treatment train, which importantly simplifies operations and improves quality control in the manufacture of high purity water for down-hole applications.

Other important but more specific objectives reside in the provision of various embodiments for an improved water treatment process for production of high purity water for down-hole use in heavy oil recovery, which embodiments may:

- in one embodiment, eliminate the requirement for flash separation of the high pressure steam to be utilized downhole from residual hot pressurized liquids;
- eliminate the generation of softener sludges;
- minimize the production of undesirable liquid or solid waste streams;
- minimize operation and maintenance labor requirements;
- minimize maintenance materiel requirements;
- minimize chemical additives and associated handling requirements;
- increase reliability of the OTSG's, when used in the process;
- decouple the de-oiling operations from steam production operations; and
- reduce the initial capital cost of water treatment equipment.

Other important objectives, features, and additional advantages of the various embodiments of the novel process disclosed herein will become apparent to the reader from the foregoing and from the appended claims and the ensuing detailed description, as the discussion below proceeds in conjunction with examination of the accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWING

In order to enable the reader to attain a more complete appreciation of the novel water treatment process disclosed and claimed herein, and the various embodiments thereof, and of the novel features and the advantages thereof over prior art processes, attention is directed to the following detailed description when considered in connection with the accompanying figures of the drawing, wherein:

FIG. 1 shows one typical prior art process, namely a generalized process flow diagram for a physical-chemical water treatment process configured for use in heavy oil recovery operations.

FIG. 2 shows another prior art process, namely a generalized process flow diagram for a physical-chemical water treatment process as used in a steam assisted gravity drainage (SAGD) type heavy oil operation.

FIG. 3 shows yet another prior art physical-chemical treatment process scheme, also as it might be applied for use in steam assisted gravity drainage (SAGD) type heavy oil recovery operations.

FIG. 4 shows one embodiment of an evaporation based water treatment process, illustrating the use of a seeded slurry evaporation based process in combination with the use of packaged boilers for steam production, as applied to heavy oil recovery operations.

FIG. 5 shows another embodiment for an evaporation based water treatment process for heavy oil production, illustrating the use of a seeded slurry evaporation process in combination with the use of once-through steam generators for steam production, as applied to heavy oil recovery operations, which process is characterized by feed of evaporator distillate to once-through steam generators without the necessity of further pretreatment.

FIG. 6 shows a common variation for the orientation of injection and gathering wells as utilized in heavy oil recovery, specifically showing the use of horizontal steam injection wells and of horizontal oil/water gathering wells, as often employed in a steam assisted gravity drainage heavy oil gathering project.

FIG. 7 shows the typical feedwater quality requirements for steam generators which produce steam in the 1000 pounds per square inch gauge range, or thereabouts, for conventional steam boiler installations.

FIG. 8 shows the typical feedwater quality requirements for steam generators which produce steam in the 1000 pounds per square inch gauge range, or thereabouts, for once-through type steam generator installations.

FIG. 9 provides a simplified view of a vertical tube falling film evaporator operating in a seeded slurry mode in the treatment of produced water from heavy oil operations, for production of distillate for reuse in once through steam generators or in conventional steam boilers.

FIG. 10 shows further details of the use of evaporators operating in a seeded slurry mode, illustrated by use of falling film evaporators, and indicates selected injection points for acidification of the feedwater and for control of pH in the evaporator via optional injection of a selected base such as sodium hydroxide.

FIG. 11 illustrates the solubility of silica in water as a function of pH at 25° C. when such silica species are in equilibrium with amorphous silica, as well as the nature of such soluble silica species (molecule or ion) at various concentration and pH ranges.

FIG. 12 diagrammatically illustrates functional internal details of the operation of a falling film evaporator operating in a seeded slurry mode, which evaporator type would be useful in the evaporation of produced waters from heavy oil production; details illustrated include the production of steam from a falling brine film, by a heat exchange relationship from condensation of steam on a heat exchange tube, and the downward flow of such steam condensate (distillate) by gravity for the collection of such condensate (distillate) above the bottom tube sheet of the evaporator.

The foregoing figures, being merely exemplary, contain various elements that may be present or omitted from actual process implementations depending upon the circumstances. An attempt has been made to draw the figures in a way that illustrates at least those elements that are significant for an understanding of the various embodiments and aspects of the invention. However, various other elements of the unique process methods, and the combination of apparatus for carrying out the methods, are also shown and briefly described to enable the reader to understand how various features, including optional or alternate features, may be utilized in order to provide an efficient, low cost process design which can be implemented in a desired throughput size and physical configuration for providing optimum water treatment plant design and operation.

DESCRIPTION

Many steam assisted heavy oil recovery schemes, such as a steam assisted gravity drainage (SAGD) heavy oil recovery process injection and recovery well arrangements of the type depicted in FIG. 6, most efficiently utilize a 100% quality steam supply 70. It would therefore be desirable to produce such a steam supply by an efficient process scheme such as I have found may be provided by evaporation based heavy oil produced water treatment method(s). Various embodiments and details of such evaporation based produced water treatment method(s) are depicted in FIGS. 4, 5, 6, 9, 10 and 12.

As depicted in FIG. 6, in a SAGD process, horizontal injection wells 16' and horizontal oil/water gathering wells 30' are advantageously utilized spaced apart within an oil bearing formation 20. As particularly illustrated in FIGS. 4 and 5, a process for the use of an evaporation based water

treatment system **120** has been developed to treat produced water, in order to produce high quality steam for use in further heavy oil recovery. Conceptually, such an evaporative water treatment process may, in one embodiment, be situated process wise—that is, water flow wise—between the point of receipt of a de-oiled produced water stream **46** and the point of steam injection at well head **48** of injection well **16**. The process, in combination with the steam injection well **16**, oil recovery well **30**, and related oil water separation equipment **32** and de-oiling equipment **40**, and boilers **80** as shown in FIG. **4**, or alternately, once through steam generators **12** as shown in FIG. **5**, can substantially reduce capital costs and can minimize ongoing operation and maintenance costs of heavy oil recovery installations. Boilers **80** may be packaged, factory built boilers of various types or field assembled boilers with mud and steam drums and water wall piping, or more generally, conventional steam boilers. In some locales, such as northern Canada, the possibility of elimination of the need for handling of waste sludges and other waste streams made possible by the evaporation based water treatment system **120** may be especially important, since it may be difficult to work with such waste materials during the extremely cold winter months.

It has been observed that it may be desirable in some instances to use a packaged boiler **80** to produce the required steam **70**, rather than to utilize a traditional once-through type steam generator **12** to produce 80% quality steam **14** and then utilize separator(s) **130** to separate steam **132** from liquid **134**. It is noteworthy in such an economic process evaluation that packaged boilers **80** are often less expensive on a capital cost basis and on an operating cost basis than once-through type oil-field steam generators **12**. Also, package boilers can be utilized to produce pure steam **70**, and thus produce only a minimal liquid blowdown stream **110**. Also, as shown in FIGS. **4** and **5**, boiler blowdown stream can be either sent to the evaporator feed tank **210**, or injected into the sump reservoir **152** of evaporator **140**, such as via line **111**, or into a recirculating brine via line **111'**. One type of packaged boiler suitable for use in the process described herein is a water tube boiler having a lower mud drum and an upper steam drum and water cooled sidewalls substantially extending therebetween in a manner which encloses a combustion chamber. However, most such packaged boilers require a much higher quality feed water **80F** than is the case with requirements for feedwater **12F** for a once-through type steam generator. As a result, in one embodiment, the process disclosed herein includes an evaporation unit **140** based approach to packaged boiler **80** feedwater **80F** pretreatment. In other words, the de-oiled produced water **46** generated can be advantageously treated by an evaporative process operating in a seeded slurry mode, particularly if the oil in the de-oiled produced water is reduced reliably to a selected low level of less than about **20** parts per million, or more preferably to less than about **10** parts per million, and provides a significantly improved method for produced water treatment in heavy oil production.

An oil/water mixture **22** is pumped up through oil gathering wells **30**. The oil/water mixture **22** is sent to a series of oil/water separators **32**. An oil product **34** is gathered for further conditioning, transport, and sale. The produced water **36** which has been separated from the oil/water mixture **22** is then sent to a produced water de-oiling step **40**, which may be accomplished in dissolved air flotation units with the assistance of the addition of a de-oiling polymer **42**, or by other appropriate unit processes, to achieve a preselected low residual oil level such as less than **20** parts per million.

In the water treatment method disclosed herein, the de-oiled produced water **46** is treated and conditioned for feed to

one or more mechanical vapor recompression evaporator units **140** (normally, multiple redundant units) to concentrate the incoming produced water stream **46**. The necessary treatment and conditioning prior to the evaporator unit **140** can be efficiently accomplished, but may vary somewhat based on feedwater chemistry—i.e. the identity and distribution of various dissolved and suspended solids—and on the degree of concentration selected for accomplishment in evaporator units **140**.

In one embodiment, it may be necessary or appropriate to add acid by line **144**, or at an appropriate point upstream of the feed tank **210** when desired such as via line **146'**. A suitable acid may be sulfuric acid or hydrochloric acid, which is effective to lower the pH sufficiently so that bound carbonates are converted to free gaseous carbon dioxide, which is removed, along with other non-condensable gases **148** dissolved in the feedwater **46** such as oxygen and nitrogen, in an evaporator feedwater deaerator **150**. However, use of acid **144** in this manner is optional, and can sometimes be avoided if feedwater chemistry and the concentration limits of scale forming species are sufficiently low at the anticipated concentration factor utilized in evaporator **140**. For pH control, as seen in FIG. **10**, it may be useful to add a selected base such as caustic **232** to the concentrated brine recirculating in the evaporator **140**, which can be accomplished by direct injection of a selected base such as caustic **232** into the sump **141**, as indicated by line **157**, or by feed of a selected base such as caustic **232** into the suction of recirculation pump **153**, as indicated by line **159**. However, if the produced water contains an appreciable amount of calcium and sulfate, the mechanical vapor recompression evaporator **140** may in one embodiment be operated using a calcium sulfate seeded-slurry technique, normally in a near neutral pH range. That mode of operation can be made possible by the substantial elimination of carbonate alkalinity before the feedwater is introduced into the evaporator **140**. Then, the evaporator **140** may be operated a seeded-slurry mode wherein calcium sulfate and silica co precipitated recirculating seed crystals, which avoids scaling of the heat transfer surfaces.

At feedwater heat exchanger, the feedwater pump **149** is used to provide sufficient pressure to send feedwater from the evaporator feed tank **210** through the feedwater heat exchanger **148**, prior to the deaerator **150**. In the opposite direction, the distillate pump **143** moves distillate **180** through the feedwater heat exchanger **148**, so that the hot distillate is used to heat the feedwater stream directed toward the deaerator **150**.

The conditioned feedwater **151** is sent as feedwater to evaporator **140**. The conditioned feedwater **151** may be directed to the inlet of recirculation pump **153**, or alternately, directed to the sump **141** of evaporator **140** as indicated by broken line **151'** in FIG. **10**. Concentrated brine **152** in the evaporator **140** is recirculated via pump **153**, so only a small portion of the recirculating concentrated brine is removed on any one pass through the evaporator **140**. In the evaporator **140**, the solutes in the feedwater **46** are concentrated via removal of water from the feedwater **46**. As depicted in FIGS. **10** and **12**, an evaporator **140** is in one embodiment provided in a falling film configuration wherein a thin brine film **154** is provided by distributors **155** and then falls inside of a heat transfer element, e.g. tube **156**. A small portion of the water in the thin brine film **154** is extracted in the form of steam **160**, via heat given up from heated, compressed steam **162** which is condensing on the outside of heat transfer tubes **156**. Thus, the water is removed in the form of steam **160**, and that steam is compressed through the compressor **164**, and the compressed steam **162** is condensed at a heat exchange tube **156**

in order to produce yet more steam **160** to continue the evaporation process. The condensing steam on the outer wall **168** of heat transfer tubes **156**, which those of ordinary skill in the evaporation arts and to which this disclosure is directed may variously refer to as either condensate or distillate **180**, is in relatively pure form, low in total dissolved solids. In one embodiment, such distillate contains less than 10 parts per million of total dissolved solids of non-volatile components. Since, as depicted in the embodiments shown in FIGS. **4**, **5**, **9**, and **10**, a single stage of evaporation is provided, such distillate **180** may be considered to have been boiled, or distilled, once, and thus condensed but once.

Prior to the initial startup of the evaporator **140** in the seeded-slurry mode, the evaporator, which in such mode may be provided in a falling-film, mechanical vapor recompression configuration, the fluid contents of the unit are "seeded" by the addition of calcium sulfate (gypsum). The circulating solids within the brine slurry serve as nucleation sites for subsequent precipitation of calcium sulfate **272**, as well as silica **274**. Such substances both are precipitated as an entering feedwater is concentrated. Importantly, the continued concentrating process produces additional quantities of the precipitated species, and thus creates a continuing source of new "seed" material as these particles are broken up by the mechanical agitation, particularly by the action of the recirculation pump **153**.

In order to avoid silica and calcium sulfate scale buildup in the evaporator **140**, calcium sulfate seed crystals **272** are continuously circulated over the wetted surfaces, i.e., the falling film evaporator tubes **156**, as well as other wetted surfaces in the evaporator **140**. Through control of slurry concentration, seed characteristics, and system geometry, the evaporator can operate in the otherwise scale forming environment. The thermo chemical operation within the evaporator **140** with regard to the scale prevention mechanism is depicted in FIG. **12**. As the water is evaporated from the brine film **154** inside the tubes **156**, the remaining brine film becomes super saturated and calcium sulfate and silica start to precipitate. The precipitating material promotes crystal growth in the slurry rather than new nucleation that would deposit on the heat transfer surfaces; the silica crystals attach themselves to the calcium sulfate crystals. This scale prevention mechanism, called preferential precipitation, has a proven capability to promote clean heat transfer surfaces **260**. The details of one advantageous method for maintaining adequate seed crystals in preferentially precipitation systems is set forth in U.S. Pat. No. 4,618,429, issued Oct. 21, 1986 to Howard R. Herrigel, the disclosure of which is incorporated into this application in full by this reference.

It is to be understood that the falling film evaporator **140** design is provided only for purposes of illustration and thus enabling the reader to understand the water treatment process(es) taught herein, and is not intended to limit the process to the use of such evaporator design, as those in the art will recognize that other designs, such as, for example, a forced circulation evaporator, or a rising film evaporator, may be alternately utilized with the accompanying benefits and/or drawbacks as inherent in such alternative evaporator designs.

In any event, in a falling film evaporator embodiment, the distillate **180** descends by gravity along tubes **156** and accumulates above bottom tube sheet **172**, from where it is collected via condensate line **174**. A small portion of steam in equilibrium with distillate **180** may be sent via line **172** to the earlier discussed deaerator **150** for use in mass transfer, i.e., heating and steam stripping descending liquids in a packed tower to remove non-condensable gases **148** such as carbon dioxide. However, the bulk of the distillate **180** is removed as

a liquid via line **180'**, and may optionally be sent for further treatment in a distillate treatment plant, for example such as depicted in detail in FIG. **4**, or as merely depicted in functional form as feed **181_F** for plant **181** in FIG. **5**, to ultimately produce a product water **181_P** which is suitable for evaporator feedwater, such as feedwater **80_F'** in the case where packaged boilers **80** are utilized as depicted in FIG. **4**. The plant **181** also normally produces a reject stream **181_R** which may be recycled to the evaporator feed tank **210** or other suitable location for reprocessing or reuse. As shown in the embodiment set forth in FIG. **5**, the distillate treatment plant **181** is optional, especially in the case of the use of once through steam generators, and in such instance the distillate **180** may often be sent directly to once-through steam generators as feedwater **12_F'** (as distinguished from the higher quality from feedwater **12_F** discussed hereinabove with respect to prior art processes) for generation of 80% quality steam **14**. Also, as shown in FIG. **4**, a distillate treatment plant **181** may also be optional in some cases, depending on feedwater chemistry, and in such cases, distillate **180** may be fed directly to boiler **80** as indicated by broken line **81**.

In an embodiment where boilers **80** are used rather than once through steam generators **12**, however, it may be necessary or desirable to remove the residual organics and other residual dissolved solids from the distillate **180** before feed of distillate **180** to the boilers **80**. For example, as illustrated in FIG. **4**, in some cases, it may be necessary to remove residual ions from the relatively pure distillate **180** produced by the evaporator **140**. In most cases the residual dissolved solids in the distillate involve salts other than hardness. In one embodiment, removal of residual dissolved solids can be accomplished by passing the evaporator distillate **180**, after heat exchanger **200**, through an ion exchange system **202**. Such ion-exchange systems may be of mixed bed type or include an organic trap, and directed to remove the salts and/or organics of concern in a particular water being treated. In any event, regenerant chemicals **204** will ultimately be required, which regeneration results in a regeneration waste **206** that must be further treated. Fortunately, in the process scheme described herein, the regeneration waste **206** can be sent back to the evaporator feed tank **210** for a further cycle of treatment through the evaporator **140**.

In another embodiment, removal of residual dissolved solids can be accomplished by passing the evaporator distillate **180** through a heat exchanger **200'** and then through electro-deionization (EDI) system **220**. The EDI reject **222** is also capable of being recycled to evaporator feed tank **210** for a further cycle of treatment through the evaporator **140**.

The just described novel combination of process treatment steps produces feedwater of sufficient quality, and in economic quantity, for use in packaged boilers **80** in heavy oil recovery operations. Advantageously, when provided as depicted in FIG. **4** a single liquid waste stream is generated, namely evaporator blowdown **230**, which contains the concentrated solutes originally present in feedwater **46**, along with additional contaminants from chemical additives (such as regeneration chemicals **204**). Also, in many cases, even the evaporator blowdown **230** can be disposed in an environmentally acceptable manner, which, depending upon locale, might involve injection in deep wells **240**. Alternately, evaporation to complete dryness in a zero discharge system **242**, such as a crystallizer or drum dryer, to produce dry solids **244** for disposal, may be advantageous in certain locales.

Various embodiments for new process method(s), as set forth in FIGS. **4** and **5** for example, are useful in heavy oil production since they generally offer one or more of the following advantages: (1) eliminate many physical-chemical

treatment steps commonly utilized previously in handling produced water (for example, lime softening, filtering, ion exchange systems, and certain de-oiling steps are eliminated); (2) result in lower capital equipment costs, since the evaporative approach to produced water treatment results in a zero liquid discharge system footprint size that is about 80% smaller than that required if a prior art physical-chemical treatment scheme is utilized, as well as eliminating vapor/liquid separators and reducing the size of the boiler feed system by roughly 20%; (3) result in lower operating costs for steam generation; (4) eliminate the production of softener sludge, thus eliminating the need for the disposal of the same; (5) eliminate other waste streams, thus minimizing the number of waste streams requiring disposal; (6) minimize the material and labor required for maintenance; (7) reduce the size of water de-oiling equipment in most operations; and (8) decouple the de-oiling operations from the steam generation operations.

One of the significant economic advantages of using a vertical tube, falling film evaporator such as of the type described herein is that the on-line reliability and redundancy available when multiple evaporators are utilized in the treatment of produced water. An evaporative based produced water treatment system can result in an increase of from about 2% to about 3% or more in overall heavy oil recovery plant availability, as compared to a produced water treatment system utilizing a conventional prior art lime and clarifier treatment process approach. Such an increase in on-line availability relates directly to increased oil production and thus provides a large economic advantage over the life of the heavy oil recovery plant.

In the process disclosed herein, the evaporator **140** is designed to produce high quality distillate (typically 2-5 ppm non-volatile TDS) which, after temperature adjustment to acceptable levels in heat exchangers **200** or **200'** (typically by cooling to about 45° C., or lower) can be fed directly into polishing equipment (EDI system **220**, ion exchange system **202**, or reverse osmosis system **224**) for final removal of dissolved solids. The reject stream **221** from the reverse osmosis system can be recycled to the evaporator feed tank **210** for further treatment. Likewise, the reject from the EDI system may be recycled to the evaporator feed tank **210** for further treatment. Similarly, the regenerant from most ion exchange processes **202** may be recycled to the evaporator feed tank **210** for further treatment. The water product produced by the polish equipment just mentioned is most advantageously used as feedwater for the packaged boiler **80**. That is because in the typical once-through steam generator **12** used in oil field operations, it is normally unnecessary to incur the additional expense of final polishing by removal of residual total dissolved solids from the evaporator distillate stream **180**. In some applications, final polishing is not necessary when using conventional boilers **80**. This can be further understood by reference to FIG. 6, where a typical boiler feed water chemistry specification is presented for (a) packaged boilers, and (b) once-through steam generators. It may be appropriate in some embodiments from a heat balance standpoint that the de-oiled produced waters **46** fed to the evaporator for treatment be heated by heat exchange with the distillate stream **180**. However, if the distillate stream is sent directly to once-through steam generators **12**, then no cooling of the distillate stream **180** may be appropriate. Also, in the case of once-through steam generators **12**, it may be necessary or appropriate to utilize a plurality of flash tanks F1, etc., in the manner described above with reference to FIG. 2.

Also, as briefly noted above, but significantly bears repeating, in those cases where the EDI system **220** is utilized for

polishing, the membrane reject stream includes an EDI reject stream **222** that is recycled to be mixed with the de-oiled produced water **46** in the evaporator feed tank **210** system, for reprocessing through the evaporator **140**. Similarly, when reverse osmosis is utilized the a membrane reject stream includes the RO reject stream which is recycled to be mixed with the de-oiled produced water **46** in the evaporator feed tank **210** system, for reprocessing through the evaporator **140**. Likewise, when ion-exchange system **202** is utilized, the regenerant waste stream **206** is recycled to be mixed with the de-oiled produced water **46** in the evaporator feed tank system, for reprocessing through the evaporator **140**.

Again, it should be emphasized that the blowdown **230** from the evaporator **140** is often suitable for disposal by deep well **240** injection. Alternately, the blowdown stream can be further concentrated and/or crystallized using a crystallizing evaporator, or a crystallizer, in order to provide a zero liquid discharge **242** type operation. This is an important advantage, since zero liquid discharge operations may be required if the geological formation is too tight to allow water disposal by deep well injection, or if regulatory requirements do not permit deep well injection.

Many produced waters encountered in heavy oil production are high in silica, with values that may range up to about 200 mg/l as SiO₂, or higher. Use of a seeded slurry operational configuration in evaporator **140** co-precipitates silica with precipitating calcium sulfate, to provide a process design which prevents the scaling of the inner surfaces **260** of the heat transfer tubes **156** with the ever-present silica. This is important, since silica solubility must be accounted for in the design and operation of the evaporator **140**, in order to prevent silica scaling of the heat transfer surfaces **260**.

Since the calcium hardness and sulfate concentrations of many produced waters is low (typically 20-50 ppm Ca as CaCO₃), it is possible in many cases to operate the evaporators **140** with economically efficient concentration factors, while remaining below the solubility limit of calcium sulfate, assuming proper attention to feedwater quality and to pre-treatment processes.

It is to be appreciated that the water treatment process described herein for preparing boiler feedwater in heavy oil recovery operations is an appreciable improvement in the state of the art of water treatment for oil recovery operations. The process eliminates numerous of the heretofore encountered waste streams, while processing water in reliable mechanical evaporators, and in one embodiment, in mechanical vapor recompression ("MVR") evaporators. Polishing, if necessary, can be accomplished in ion exchange, electro-deionization, or reverse osmosis equipment. The process thus improves on currently used treatment methods by eliminating most treatment or regeneration chemicals, eliminating many waste streams, eliminating some types of equipment. Thus, the complexity associated with a high number of treatment steps involving different unit operations is avoided.

In the improved water treatment method, the control over waste streams is focused on a the evaporator blowdown, which can be conveniently treated by deep well **240** injection, or in a zero discharge system **242** such as a crystallizer and/or spray dryer, to reduce all remaining liquids to dryness and producing a dry solid **244**. This contrasts sharply with the prior art processes, in which sludge from a lime softener is generated, and in which waste solids are gathered at a filter unit, and in which liquid wastes are generated at an ion exchange system and in the steam generators. Moreover, this waste water treatment process also reduces the chemical handling requirements associated with water treatment operations.

It should also be noted that the process described herein can be utilized with once through steam generators, since due to the relatively high quality feedwater—treated produced water—provided to such once through steam generators, the overall blowdown rate of as low as about 5% or less may be achievable in the once through steam generator. Alternately, as shown in FIG. 5, at least a portion of the liquid blowdown **134** from the once through steam generator **12** can be recycled to the steam generator **12**, such as indicated by broken line **135** to feed stream **12F**.

In yet another embodiment, to further save capital and operating expense, industrial boilers of conventional design may be utilized since the distillate—treated produced water—may be of sufficiently good quality to be an acceptable feedwater to the boiler, even if it requires some polishing. It is important to observe that use of such boilers reduces the boiler feed system and evaporative produced water treatment system size by twenty percent (20%), eliminates vapor/liquid separation equipment as noted above, and reduces the boiler blowdown flow rate by about ninety percent (90%).

In short, evaporative treatment of produced waters using a falling film, vertical tube evaporator is technically and economically superior to prior art water treatment processes for heavy oil production. It is possible to recover ninety five percent (95%) or more, and even up to ninety eight percent (98%) or more, of the produced water as high quality distillate **180** for use as high quality boiler feedwater (resulting in only a 2% boiler blowdown stream which can be recycled to the feed for evaporator **140**). Such a high quality distillate stream may be utilized in SAGD and non-SAGD heavy oil recovery operations. Such a high quality distillate stream may have less than 10 mg/L of non-volatile inorganic TDS and is useful for feed either to OTSGs or to conventional boilers.

The overall life cycle costs for the novel treatment process described herein are significantly less than for a traditional lime softening and ion exchange treatment system approach. And, an increase of about 2% to 3% in overall heavy oil recovery plant availability is achieved utilizing the treatment process described herein, which directly results in increased oil production from the facility. Since boiler blowdown is significantly reduced, by as much as 90% or more, the boiler feed system may be reduced in size by as much as fifteen percent (15%) or more. Finally, the reduced blowdown size results in a reduced crystallizer size when zero liquid discharge is achieved by treating blowdown streams to dryness.

Although only several exemplary embodiments of this invention have been described in detail, it will be readily apparent to those skilled in the art that the novel produced waste treatment process, and the apparatus for implementing the process, may be modified from the exact embodiments provided herein, without materially departing from the novel teachings and advantages provided by this invention, and may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. Therefore, the disclosures presented herein are to be considered in all respects as illustrative and not restrictive. It will thus be seen that the objects set forth above, including those made apparent from the preceding description, are efficiently attained. Many other embodiments are also feasible to attain advantageous results utilizing the principles disclosed herein. Therefore, it will be understood that the foregoing description of representative embodiments of the invention have been presented only for purposes of illustration and for providing an understanding of the invention, and it is not intended to be exhaustive or restrictive, or to limit the invention only to the precise forms disclosed.

All of the features disclosed in this specification (including any accompanying claims, and the drawing) may be combined in any combination, except combinations where at least some of the features are mutually exclusive. Alternative fea-

tures serving the same or similar purpose may replace each feature disclosed in this specification (including any accompanying claims, and the drawing), unless expressly stated otherwise. Thus, each feature disclosed is only one example of a generic series of equivalent or similar features. Further, while certain process steps are described for the purpose of enabling the reader to make and use certain water treatment processes shown, such suggestions shall not serve in any way to limit the claims to the exact variation disclosed, and it is to be understood that other variations, including various treatment additives or alkalinity removal techniques, may be utilized in the practice of my method.

The intention is to cover all modifications, equivalents, and alternatives falling within the scope and spirit of the invention, as expressed herein above and in any appended claims. The scope of the invention, as described herein and as indicated by any appended claims, is thus intended to include variations from the embodiments provided which are nevertheless described by the broad meaning and range properly afforded to the language of the claims, as explained by and in light of the terms included herein, or the legal equivalents thereof.

The invention claimed is:

1. A process for treatment of a produced water stream resulting from the production of oil from heavy oil reserves, said produced water stream comprising dissolved solutes including calcium, sulfate, silica, alkalinity, and non-condensable gases, and wherein said treatment comprises:

(a) acidification of said produced water stream, to remove alkalinity by conversion to free carbon dioxide;

(b) steam stripping said produced water stream to remove said non-condensable gases and said carbon dioxide produced in said alkalinity removal step;

(c) evaporation of said produced water stream to produce a slurry comprising water, dissolved solutes, calcium sulfate, and silica, to generate (i) a distillate stream at about 95% or more by volume of said produced water stream and (ii) a blowdown stream at about 5% or less by volume of said produced water stream;

(d) generating a steam stream at about 100% quality and at about 1000 pounds per square inch pressure or more from said distillate stream, and wherein said steam stream comprises at least about 70% by weight of said distillate stream, and generating a blowdown stream of about 30% or less by weight of said distillate stream.

2. The process as set forth in claim 1, wherein said steam stream comprises at least 95% by weight of said distillate stream.

3. The process as set forth in claim 2, wherein said steam stream comprises at least 98% by weight of said distillate stream.

4. The process as set forth in claim 3, where said blowdown stream is added to and mixed with said produced water stream prior to evaporation of said produced water stream.

5. The process as set forth in claim 3, wherein evaporation of said produced water stream is accomplished in a falling film evaporator.

6. The process as set forth in claim 1, wherein the produced water stream is treated with acid to lower the pH to convert alkalinity to free carbon dioxide.

7. The process as set forth in claim 1, wherein said evaporator comprises a heat transfer surface, and wherein said slurry of calcium sulfate and silica is maintained at a preselected concentration for preferential precipitation of said calcium said sulfate and said silica to said slurry rather than to said heat transfer surfaces of said evaporator.